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On High Temperature Materials: Robust LCSP as Solved for AISI 310S Alloy, and Cumulative LFR as Applied to Radiant Heater Tubes

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Abstract

Logistic Creep Strain Prediction (LCSP) is applied to predict creep curves, creep rate curves, and Larson-miller parameter (LMP) master curve. Life Fraction Rule (LFR) is used to obtain and remnant life of industrial pressure vessel tubes. Creep curves are plotted for test temperature of 650°C under applied load 100-200MPa. It matches well with the predictions of MHG equation, Ө projection, MG equation and Wilshire equation. As LCSP and LFR involve simple iterations; Microsoft Office EXCEL, WPS Spreadsheet, and Internet online fxsolver, is sufficient. Cumulative LFR is applied to obtain maximum internal hoop stress for various 1.3y periods. Predictions match with that of solid works (Dassault Systems), Pro/Engineer, Autodesk and ANSYS software. Trend of creep and creep rate curves and LMP master curves is as same as that shown by experimental curves and chart plotted for 700, 750 and 800ºC.

Keywords: *LCSP, LFR, AISI 301S, MHG, Ө Projection, MG, Wilshire Equation.*

INTRODUCTION

Engineering applications, viz., energy, aerospace, manufacture, and transport are advancing, and demands on materials. New materials are required to meet new demands posed by operating conditions, such as high temperature capability, high specific strength and improved corrosion resistance, in these high end applications. High specific strength, creep resistance and high temperature capability among other desirable properties in these high end applications [1]. Time-dependent high temperature deformation called creep is a major problem for parts manufactured for such applications. Heat resistant alloys, austenitic stainless steels and super-alloys are usual candidate materials for such applications, and are capable of withstanding creep conditions (high load less than YS and T above half of its mp). AISI 310 stainless steel (Cr 20% & Ni 25%) and its sub-grades provide such functions. Table 1 enlists some of the applications where this alloy is already in use [2]. Real time creep tests, done on Mayes constant load mechatronics creep testing machines, are time-consuming (10000-200000hours) and hence, models are very popular for creep analysis. Modeling and simulation is basis of this research article, and is applied in detail to creep-rupture behavior of AISI 310S alloy by Robust LCSP method, and also to life prediction of components made up of this super-alloy stainless steel by Cumulative LFR [3]. Creep models are very effective in predicting creep curves, creep rate curves, steady state creep plots, stress rupture plots, MG plot, deformation maps, fracture maps, LMP master curve and remnant life assessment. Some models apply regression analysis of creep data followed by interpolation and extrapolation [3−7]. Many complicated models based on damage mechanics as well as ductility exhaustion concept are used by many mechanical stress analysis and engineering design software codes [8−10]. As creep is an engineering problem, its assessment ends at stress and strain at various locations of the component, and remnant life estimation. LMP and LFR are usually used for component life estimation [11,12].

Table 1: *Commercial grades of Cr25-Ni20 super-alloy stainless steel.*

AISI 310 C0.25-Cr25-Ni20	Oil refinery, Thermal power, Gas turbine, Furnace linings, Open hearth rollers, Kiln linings, Burner parts, For carrying cryogenic engines fuels for aerospace. It finds application like AISI 600 super alloy
AISI 310H C0.10-Cr25-Ni20	Materials choice for high temperature applications and are used at 800-900°C, above T at which AISI AISI 321 is effective.
AISI 310L C0.03-Cr25-Ni20	Like AISI304L, it is used for corrosive parts, eg., urea manufacture. It offers superior oxidation resistance, and higher fatigue strength and excel in sub-zero T.
AISI 310S C0.08-Cr25-Ni20	Moist corrosion low and finds application in Furnace, Oil burner. Carburising boxes, Heat Treatment baskets and jigs, Heat exchangers, Welding filler wire and electrodes. It is good aqueous corrosion resistance, similar to that of Grade 316.
AISI 310Si C0.20-Cr25-Ni20 –N0.11-Si2.0	Refractory supports, Retorts linings, Oven linings, Chemical process industry containers for hot concentrated acids, ammonia, and sulfur dioxide, and Food processing industry- used in contact with hot acetic and citric acid.

MATERIALS AND METHOD

Sheets of AISI 310S alloy was supplied by Indian Public Sector Stainless Steel Company (Salem Steel Plant, Steel Authority of India Limited, Ministry of Steel, Government of India). Fig.1 shows typical industrial component (radiant heater pipe) made on AISI 310S alloy. Table 2 gives typical properties of this heat resistant alloy. Systematic creep, stress-rupture, oxidation and hot corrosion tests were done and the results were already published elsewhere [1]. Well defined creep tests were conducted at 700ºC, 750ºC and 800ºC under applied loads 40-150MPa. Fig.2 shows creep-rupture experimental set up. This data is basis for obtaining correlations (regression equations) and constants for robust Logistic Creep Strain Prediction (LCSP). Table 3 provides mainly LCSP equations and calculations. Though plots not provides, Manson-Haferd-Grounes (MHG) extrapolation, ϴ projection (NPL, UK), Monkman-Grant (MG) interpolation and Wilshire equations provided same results [3,11]. Engineering tool LCSP is robust, meaning that similar reliability can be expected from the predictions as would be expected from creep rupture models. The best feature is, however, that this is accomplished utilizing a minimum amount of data. Some of the strain models presented have been verified with creep data withheld from the initial model optimization. Deliberate aim of keeping the modeling tools simple will hopefully make them more attractive to the design engineer and the life management expert. The simplicity, accuracy and robustness in prediction are in itself the driving force and ultimate aim of this work. Table 4 shows the method of Life Fraction Rule (LFR) calculations. Though routine method, it was applied for completeness of research on this alloy.

Figure 1: *Typical component made up of AISI 310S alloy.*

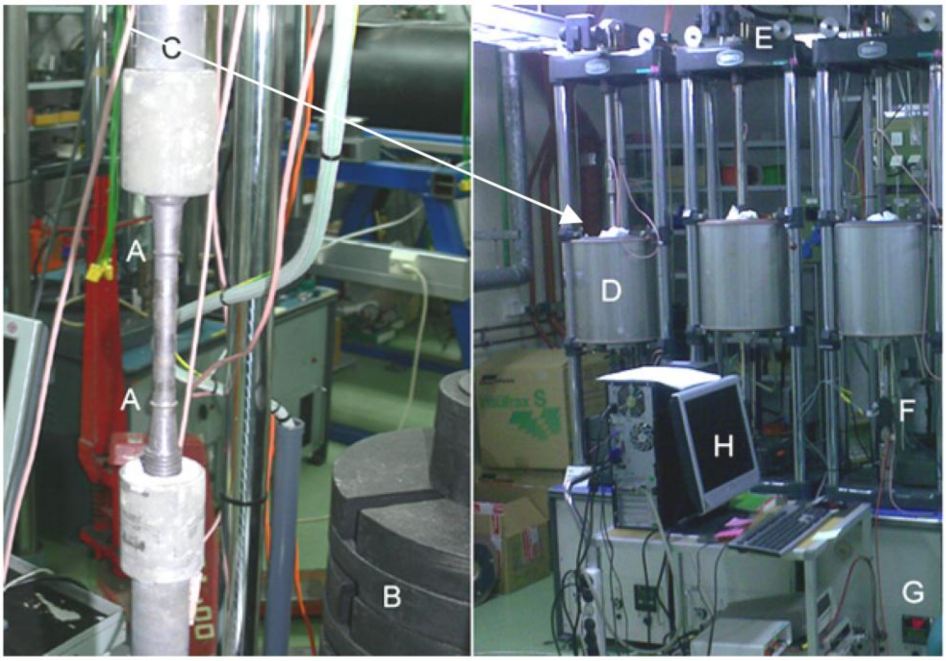

Figure 2: *Mayes constant load mechatronics creep testing machine. A-Creep specimen ridges for extensometers, B-Loading weights, C-Upper pull rod, D-Furnace, E-Lever mechanism, F-Displacement transducer, G-Eurotherm Temperature controller, H-Data acquisition computer.*

Table 2: *Typical properties of AISI 310S austenitic stainless steel.*

Chemical and Metallurgical								Mechanical and Physical	
C	Mn	Si	P	S	Ni	Cr	Fe	UTS Mpa	515 (1150/cw)
0.14	0.98	0.76	0.03	0.009	18.53	24.84	Balance	0.2%PS	205Mpa
$Cr_{Equivalent}$=Cr+2Si+1.5Mo+5V+5.5Al+1.75Nb+1.5Ti+0.75W								Elongation	40%
$Ni_{Equivalent}$= (Ni) + (Co) + 0.5(Mn) + 0.3(Cu) + 25(N) + 30I								Hardness	$95R_B$
As Cr_{Eq}=31 and Ni_{Eq}=23.4; 310S is γ FCC (with <5% δ BCC).								ρ @ 20°C	$78x10^{-8}\Omega m$
Nv=0.66+1.71Co+2.66Fe+4.66(Cr+Mo+W)+5.66V+6.66Zr+10.66N								Cp	0.5 J/g/°C
If Electron Vacancy No, Nv>2.52, the alloy should form sigma.								$k_{thermal}$	14.24W/m/°C
Nv=2.88 for 310S alloy, So, it forms σ around 700-800°C.								ε_{linear}	$15.90x10^{-6}$/°C

RESULTS AND DISCUSSION

Creep curves developed by LCSP are shown in Fig.3, which show all 3 regimes. In stage I, primary or transient creep, the curve is concave starting with an initial strain addition (ε_o) right after loading. Stage I can be considered as a hardening stage. In next, stage II, secondary creep, steady state or minimum rate creep, strain is linear function of time. In stage III, tertiary creep, curve is convex ending at fracture or rupture due to damage accumulation, and necking. Duration and extent of strain accumulated in different stages naturally depends on T and σ. Derivative plot of creep curve is bath tub shaped curve, where minimum or horizontal line of the curve is minimum creep rate (see Fig.4), or the steady state strain rate of the deformation maps. There is a close relationship between minimum creep rate and the time to rupture, the Monkman-Grant relationship. LCSP modeling tool assessed creep-rupture within the scope of this thesis are targeted at solving the challenges of the dislocation creep range. Also, most high temperature engineering structures such as steam lines, boilers, turbines operate in this. Extrapolation to low σ of high T steam mixer assessed is diffusion dominated, and data at high σ for the nuclear spent fuel stainless steel canister is again crossing over into the power law break down range. Rupture data is well presented in the form of Larson-Miller Parameter (LMP) master curve (Fig.5). When cumulative Life Fraction Rule (LFR) is applied to fired radiant heater pressure tube, Table 5 is obtained.

Table 3: *Equations used in Robust LCSP modeling for AISI 310S stainless steel.*

Equation	Description
Logistic Creep Strain Prediction (LCSP) of Holmstrom– tool for robust creep strain prediction (predicts well "curve end point", ie, time to rupture) $\ln t_\varepsilon = \frac{\ln t_r + c}{1+\left(\frac{\ln\varepsilon}{x}\right)^p}$-c, $\ln\varepsilon_t = \left(\frac{\ln t_r + c}{\ln t_\varepsilon + c}-1\right)^{1/p}$ x, $\dot{\varepsilon}$ = -UOTE to, $x = u + v.\ln\sigma + \frac{w}{T+273}$, $p = q + r.\ln\sigma + \frac{s}{T+273}$	t_r – time to rupture, ε- creep strain; x, p, c – fitting factors; ε_t – strain at time t, t_ε – time at strain ε; m, n – functions of time to strain; σ-applied stress, T-Temperature; u, v, w, q, r, s – material specific constants
Manson-Haferd-Grounes (MHG) strain model : engineering tool for creep strain prediction (does not predicts t_r) $MHG = \frac{\ln t_\varepsilon - C'}{T} = F(T, \sigma, \varepsilon)$, $\frac{\ln t_\varepsilon - c'}{T} = l' + m'\ln(\sigma)^{x'} + n'\ln(\varepsilon)^{y'}$	c'-constant, t_ε –time to strain, F(T,σ,ε) – multi-linear combination of T, σ, and ε; l', m', n', x' and y' – fitting constants, x' and y' – low non-negative integers
ϴ projection method (National Physical Laboratory of UK) $E_c = \varepsilon_o + \theta'\left(1-e^{-\theta'' t}\right) + \theta'''\left(e^{\theta'''' t}-1\right)\varepsilon_c$ $= \varepsilon_o + A\,(= \theta'\left(1-e^{-\theta'' t}\right)] + B[= \theta'''\left(e^{\theta'''' t}-1\right)]$ $\ln\theta's = a' + b'T + c''\sigma + d\sigma T$ Creep-Rupture data, on regression analysis gives ϴ's.	ε_o-initial strain before creep occurs, ϴ's – experimentally determined constants; a', b', c'' and d – material constants; A-creep strain in I stage, B- creep strain in III stage. Using ϴ's, ε_c=1%, ε_o=0,and simulation, $t=t_r$ can be obtained.
Monkman-Grant (MG) extrapolation and interpolation $t_r = k\dot{\varepsilon}^{-r'}$(or) $\ln t_r = \ln k - r'\ln\dot{\varepsilon}$	k, r'-material constants, both are sensitive to T and σ.
Wilshire equation for time to rupture. $\ln\left(\frac{\sigma}{\sigma_{UTS}}\right) = -k'\left(t_r e^{-\frac{Q_c}{RT}}\right)^{u'}$. Equation for strain rate is - t_r replaced by $\dot{\varepsilon}_m$	*k', u'* - constants obtained by fitting to the test data, *Qc*-apparent activation energy, σ_{UTS} -ultimate tensile strength at specified T.
Microsoft Office Excel and WPS Spreadsheet were used to LCSP equations by iterative procedure to plot creep curves and also to obtain stress rupture data. Creep-rupture experimental data available at 700, 750 and 800°C was used to obtain various LCSP constants(x= -4, p=6, c=20).	

Table 4: *Manipulation of remnant life for AISI 310S radiant tubes.*

For selected fired heater radiant tubes made up of AISI 310S stainless steel, outer diameter 170mm and initial thickness 6.5mm. If service period approximately 8y, then 8yX365.25dX24h=70128h operating life. By considering creep design life 100000h, internal pressure 4MPa, furnace completed ~70% life, tubes are subject to a metal thinning rate 0.15mm/y from, with combined internal corrosion and external oxidation, calculations are done with following equations	
Equation	Description
$\sigma = \frac{P_o}{2}\left(\frac{D_o}{t_e}-1\right)$, $t_e = t_i - LFxMTR$	σ-stress (now tube internal hoop stress), P_o-tube internal operating pressure, Do-tube outer diameter, t_i-tube initial thickness, t_e-tube thickness at end of period, LF-life fraction, MTR – metal thinning rate
As YS (measured as 0.2%PS)=125MPa at 650°C, allowable elastic strength σ_e=(2/3)YS=83MPa; permissible minimum tube thickness te(min)=3.9mm, also CLF(max)=1, $CLF_n=(1.3/t_r)+CLF_{n-1}$	

Tubes or pipes operating in creep regime undergo metal thinning over time. For a specified operating pressure and corrosion rate, fixing maximum temperature at which component last minimum period of time is must. Exact operating temperature is obtained to extend the life of the tubes or pipes. Consider an example of fired heater radiant tubes, Outside diameter (Do)=170mm, and Initial thickness (ti)=6.5mm. The furnace tubes are known to have been in service for approximately 8 years (70128h) operating life. Design for Creep life 100000h, furnace already spent 70% life. However, the tubes are subject to a metal thinning rate(MTR) of 0.15mm/y from, due to combined internal corrosion and external oxidation. Assessment is through Life Fraction Rules (LFR).

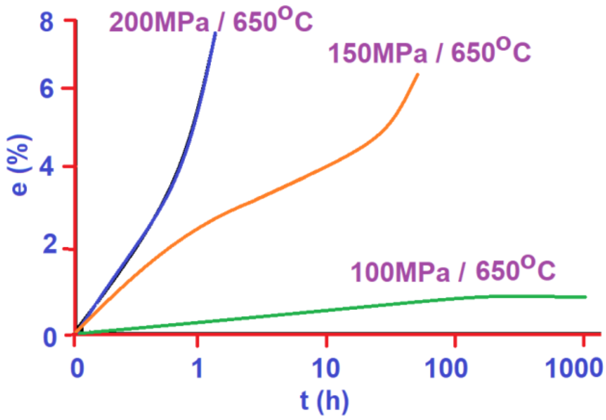

Figure 3: *LCSP creep curves plotted based on creep plots of 700, 750 and 800°C.*

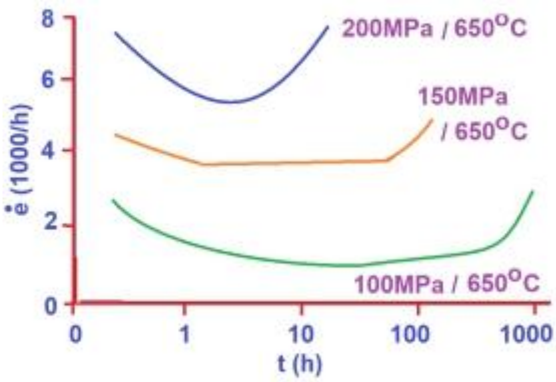

Figure 4: *LCSP plotted creep rate curves (base date Creep Plots of 700, 750 and 800°C).*

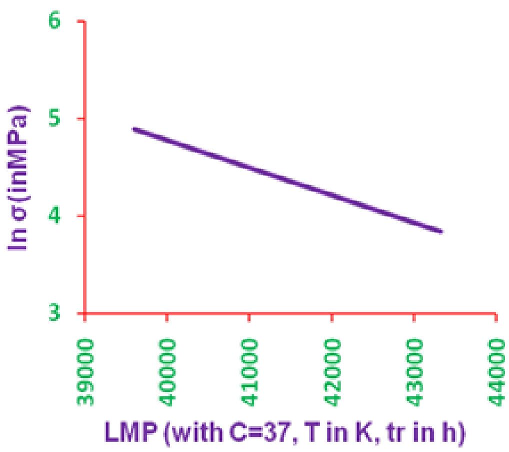

Figure 5: *LMP master curve plotted by LCSP and used in cumulative LFR calculation.*

Operation of furnace is divided into periods of time in which the pressure, metal T, and corrosion rate are considered as constant. Creep life fraction is calculated for each period. Sum of life fractions for each period is damage. Stress (S) for each period is calculated from accumulated metal loss due to MTR at each period end is used, which is conservative, as follows: S=(Po/2)[(Do/te)-1]. Minimum Larson-Miller Parameters (LMPmin) are determined from (pressure hoop) stress (S) using LMP master curves. In actual practice, neither internal P_o nor metal T is constant. However, for this calculation these parameters are treated as uniform: Period=1,Duration(increment)=1.3y(11,396); Operating pressure (Po)= 4MPa, Metal temperature (To)=60°C, Initial thickness (ti)=6.5mm; Thickness, end of period (te)=6.5–(1.3x0.15)=6.31mm, Stress (S)=(4/2)[(170/6.31)–1]=52MPa; For this S, LMPmin=43320 (C=37, tr in h, T in K), lntr=(LMP/To)-37, tr=56.5y, Life fraction (minimum) = 1.3/56.5= 0.023. The life fractions are the increment period (1.3y=11,396h) divided by the rupture time that corresponds to that period. To calculate cumulative life fraction, the above calculation is simply repeated in increments (periods) of 1.3 years, and the accumulated creep damage is the sum of the fractions for each period. At each increment (life fraction), strength of tube is checked for plastic collapse. This will occur if the tube stress (which is continually increasing due to corrosion) is equal to the allowable elastic strength (Se) at the specified operating temperature. She is equal to two-thirds of the specified minimum yield strength of the tube material at design temperature (T), ie., YS=125MPa, Se=(2/3)x125=83MPa. The minimum allowable thickness, te(min) at a design temperature of 650°C and at a design pressure of 4MPa is calculated, ie, te(min) is equal to 3.9mm. Failure will occur when either of the following conditions is reached: either by plastic collapse, when t_{actual}<te(min); or by creep rupture occurs when cumulative life fraction is greater than one. These failure criteria are highlighted in red in the following table. The remaining life is then simply calculated as cumulative period (16.9y=148148h) at which any of these two criteria are first reached, minus operating life (8y=70128h). This is equal to 16.9-8=8.9y=78020h.

Table 5: *Application of cumulative LFR for AISI 310S pressure tubes.*

No	**Cumulative Period (y)**	**Po (MPa)**	**To (°C)**	**MTR (mm/y)**	**t_e(mm)**	**S (MPa)**	**LMP (T in K, C=37, t_r in h)**	**t_r (y)**	**Cumulative LFR (1.3/CLFn +CLFn-1)**
1	1.3	4	650	0.15	6.31	52	43320	56.5	0.023
2	2.6	4	650	0.15	6.12	54	43185	48.8	0.05
3	3.9	4	650	0.15	5.93	55	43044	41.9	0.081
4	5.2	4	650	0.15	5.74	57	42902	35.9	0.117
5	6.5	4	650	0.15	5.55	59	42751	30.5	0.16
6	7.8	4	650	0.15	5.36	61	42600	25.9	0.21
7	9.1	4	650	0.15	5.17	64	42441	21.8	0.27
8	10.4	4	650	0.15	4.98	66	42275	18.2	0.341
9	11.7	4	650	0.15	4.79	69	42108	15.2	0.427
10	13	4	650	0.15	4.6	72	41928	12.5	0.531
11	14.3	4	650	0.15	4.41	75	41749	10.3	0.657
12	15.6	4	650	0.15	4.22	79	41550	8.3	0.813
13	16.9	4	650	0.15	4.03	82	41352	6.7	**1.007**
14	18.2	4	650	0.15	**3.84**	87	41153	5.4	**1.25**
15	19.5	4	650	0.15	**3.65**	91	40921	4.2	**1.557**
16	20.8	4	650	0.15	**3.46**	96	40699	3.3	**1.952**
17	22.1	4	650	0.15	**3.27**	102	40442	2.5	**2.465**
18	23.4	4	650	0.15	**3.08**	108	40189	1.9	**3.142**
19	24.7	4	650	0.15	**2.89**	116	39907	1.4	**4.05**
20	26	4	650	0.15	**2.7**	124	39597	1	**5.291**

CONCLUSION

Conclusion LCSP is robust in predicting creep curves, and component life prediction. Creep curves plotted for applied temperature of 650°C under applied load 100MPa, 150MPa and 200MPa is proved correct by Solid works FEM-based Mechanical Design software

(Dassault Systems). Cumulative LFR was applied to obtain maximum internal hoop stress for various periods, and in turn predicated component remnant life. Also, trend of creep curves and LMP chart matched well with that shown by experimental curves available for temperatures 700, 750 and 800ºC and applied stresses 40-150MPa.

REFERENCES

1. A.Kanniraj (2013), "On high-temperature materials: a case on creep and oxidation of a fully austenitic heat-resistant super alloy stainless steel sheet",*Hindawi: Journal of Materials,*, ID:124649, 6pages, dx.doi.org/10.1155/2013/124649
2. P.Panfilov, G.Kodzhaspirov(2017), "Creep and fracture of engineering materials and structures",*proceedings of the 14th international conference,* Polytechnical Publishing House, Saint Petersburg, Russia.
3. S.Holmstrom (2010), "Engineering tools for robust creep modeling", ScD Dissertation, Aalto University, Finland,
4. M.Evans (1997), "Some interpolative properties of the Monkman-Grant empirical relation in steel tubes", *International Journal of Pressure Vessels and Piping,*Volume 72, pp. 177−191.
5. M.Evans, Obtaining confidence limits for safe creep life in the presence of multi-batch hierarchical databases: an application to 18Cr–12Ni–Mo steel, Applied Mathematical Modelling, Volume 35, pp.2838–2854.
6. B.Wilshire, M.B.Bache (2009), "Cost effective prediction of creep design data for power plant steel", *Proceedings of the ECCC Creep Conference: Creep and Fracture in High Temperature Components - Design and Life Assessment Issues,* Zurich, Switzerland, pp.21−23.
7. S.Holmstrom, P.Auerkari, and S.Holdsworth (2006), "An effective parametric strain model for creep", *Proceedings of the 8th Liege Conference: Materials for Advanced Power Engineering,* Julich, Germany, pp.1309−1318.
8. K.Naumenko (2006), Modeling of high-temperature creep for structural analysis applications, PhD Thesis, University of Halle, Wittenberg, Ukraine,
9. J.F.Wen, S.T.Tu,F.Z.Xuan, X.W.Zhang, and X.L.Gao (2016), "Effects of stress level and stress state on creep ductility: evaluation of different models", *Journal of Materials Science & Technology,*Volume 32, pp.695−704.
10. C.Stewart, A hybrid constitutive model for creep, fatigue, and creep-fatigue damage;, PhD Thesis, 2013, University of Central Florida, USA
11. D.Liu,H.Li, Y.Liu (2015), "Numerical simulation of creep damage and life prediction of superalloy turbine blade, Mathematical Problems in Engineering",*Hindawi Journal,*Article ID 732502, 10 pages, dx.doi.org/10.1155/2015/732502
12. A.K. Ray, Y. N. Tiwari, S. Chaudhuri, V.R. Ranganath, S. Sivaprasad, P.K. Roy, G. Das, S.G.Chowdhury, P. Kumar, R.N.Ghosh (2002), Remaining life assessment of service exposed reheater and superheater tubes in a boiler of a thermal power plant, *High Temperature Materials and Processes,* Volume 21, pp.109−121.***:***

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